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Procedia Engineering 81 (2014) 1589 – 1594

Procedia Engineering

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11th International Conference on Technology of Plasticity, ICTP 2014, 19-24 October 2014, Nagoya Congress Center, Nagoya, Japan

Surface roughness and size effect in dendrite arm spacing at preforms of AISI 304 (1.4301) generated by laser rod end melting

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Abstract

When certain characteristics such as a low electric resistance or high wear resistance are required for parts, the first choice of material often is metal which in macro range generally allows generating the final shape by cold forming. Due to size effects, the conventional upsetting process which is well established in macro range cannot be carried out efficiently in micro range as the maximum achievable upset ratio decreases from 2.3 to less than 2 in micro range. If the advantages of cold forming are still necessary even in small products, the upsetting process has to be interrupted several times for heat treatment thus leading to a significant increase in time and handling operations making conventional upsetting inefficient in micro range. A very good opportunity to still be able to use upsetting in micro range is the laser rod end melting process. This process makes use of the fact, that when down scaling the size of a body forces related to the surface decrease less intense than forces related to the volume of the body. In this paper results of investigations on microstructure and surface roughness of dendritic preforms generated by laser rod end melting process are presented. The upset ratio realized in the master forming process in combination with the diameter of the rod strongly influences cooling and thus the secondary dendrite arm spacing within the preform. The secondary dendrite arm spacing determines the flow stress level of dendritic microstructure of preforms.

Selection and peer-review under responsibility of the Department of Materials Science and Engineering, Nagoya University

Keywords: Laser micro machining; Micro forging; Miniaturization

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1877-7058
Selection and peer-review under responsibility of the Department of Materials Science and Engineering, Nagoya University
doi:10.1016/j.proeng.2014.10.195

1. Introduction

Cold forming consists of a group of processes which are well established in macro range. This is due to certain advantages compared to other machining processes. For example, Lange (2002) states, precision forging allows reaching work piece tolerances of IT7 and if using cold work hardening wrought material, the final work piece tolerates higher load as if it would have been manufactured by a milling process. According to Burr et al. (1994), a homogenous grain structure is achieved by cold forming operation thus reducing notch effects. As a trend towards miniaturization is generally observed, knowledge which has been gained over the last decades in macro range concerning cold forming processes is not, or only with restrictions, applicable in micro range as stated by Vollertsen (2008). The conventional open die upsetting process can be considered as a basic cold forming process to determine the flow stress k_f of the work piece material, according to Lange (1988). The upsetting operation is limited in two dimensions: 1.) By reaching the maximum upset ratio s. At this point, buckling takes place. 2.) By reaching the maximum value of natural strain φ so that defects in grain structure occur, Tschaetsch (2005). As according to Meßner (1998) the maximum upset ratio in single stage upsetting is reduced from s=2.3 in macro range to values s≤2 in micro range, the upsetting process becomes inefficient if upset ratios s>2 are desired. According to Eichenhüller et al. (2010), formability is reduced when size of specimen decreases. In order to still be able to carry out upsetting in micro range efficiently, BIAS has invented the laser rod end melting process which is taking advantage of size effects and thus allowing upset ratios s*>>200 within one process step according to Stephen and Vollertsen (2011).

Nomenclature	
A_f	flattened surface area of preform
d_0	rod diameter
d_P	diameter of preform
h_P	height of preform
h_f	height of preform after upsetting operation
k_f*	flow stress level determined by open die upsetting of preform
l_0	molten upset length
P_L	laser power
r_z	surface roughness
s	upset ratio by conventional cold forming operation
s*	upset ratio by laser rod end melting process
S_D	secondary dendrite arm spacing (SDAS)
φ*	average natural strain

2. Method

2.1. Laser rod end melting

In micro range forces related to the surface of a body exceed forces related to its volume. This means that the effect of surface tension is larger than effects caused by gravitation. This size effect enables the laser rod end melting process. Herein, the end of a cylindrical rod with a diameter ranged between 0.2 mm and 1.0 mm is molten by laser beam irradiation. This first process stage is called master forming stage. The molten end of the rod forms spherical due to surface tension and sticks to the rod. This material volume is called preform. After cooling, the preform is upset by a cold forming process, defined as forming stage. The laser beam which provides the energy to melt the rod end, interacts perpendicular to the lateral surface of the rod. As the preform moves along the symmetrical axis of the rod during master forming stage, the laser beam is deflected accordingly. The quality criterion for the preform is the diameter. The preform is assumed to have a spherical geometry, therefore the measured diameter d_P equals the height h_P of the preform. The diameter of the preform is measured five times along the circumference with a micrometer caliper with a display accuracy of 1 µm. The upset ratio s* is defined as the molten upset length l_0 divided by the rod diameter d_0. Fig. 1a shows a conventional multi stage upsetting process. Fig. 1b illustrates the laser rod end melting process with beam incidence on lateral surface of the rod with a subsequent open die upsetting process.

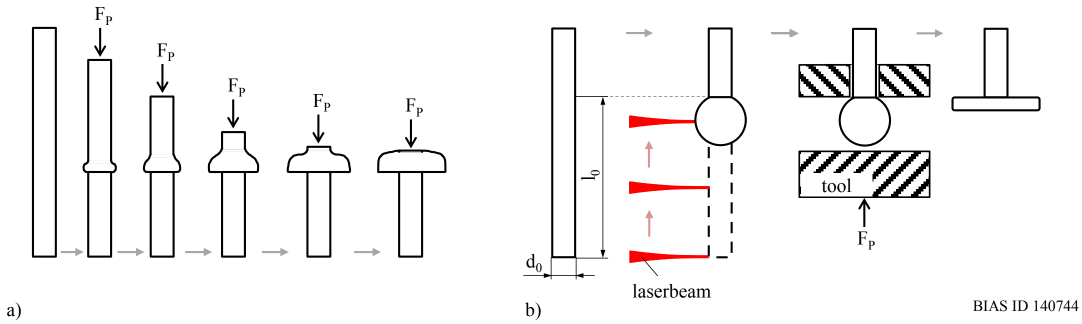

Fig. 1. (a) Conventional multi stage upsetting process; (b) laser rod end melting with subsequent upsetting operation.

2.2. Characterization of microstructure and surface topography

If using X5CrNi18-10 (AISI304) as wrought material for laser rod end melting, the micro structure of the preforms is dendritic according to Stephen et al. (2011). The significant characteristic of dendritic micro structure with respect to flow stress level is the secondary dendrite arm spacing, stated by Askeland (2006) which is detected by evaluating cross-sectional polishes. The cross-sectional polishes are etched with LB1-etchant by Lichtenegger und Bloech (composition: 100 cm³ H_2O, 20 g $(NH_4)HF_2$, 0.5 g $K_2S_2O_5$). The secondary dendrite arm spacing S_D is measured at five primary dendrites in the center of the preform so that a standard deviation of S_D can be calculated. In order to detect potential deviations within one parameter set after master forming, cross-sectional polishes of three preforms with one parameter set are investigated initially. The surface topography of the preform in both stages, directly after master forming and after upsetting, is investigated. The surface roughness and the height h_f are detected by a confocal laser microscope "VK9710" of Keyence by a fifty-fold magnification. It has to be taken into account that this is an optical detection of roughness with measuring length shorter than proposed in ISO 4288 due to size of specimen. In order to still have a reasonable measuring length, 10 parallel oriented lines with a length of 100 µm each are evaluated.

3. Experimental setup

3.1. Generating preforms by laser rod end melting

As chromium nickel steel is wide spread in industry, X5CrNi18-10 is used for all experiments as wrought material. The rod is oriented vertically and the laser beam is initially focused on the lower end of the rod. As soon as that certain part of the rod is molten, the laser beam is deflected along the movement of the up-moving preform. Due to the susceptibility for oxygen at high temperatures, argon is used as shielding gas to prevent oxidation of preforms. The specifications of the used laser system are shown in Table 1.

Table 1. Specifications of the used laser system.

Laser type and Scan head	Trumpf TruFiber 300 with Raylase TurboScan30 with Linear Translator Module LTM20				
Max. power	300 W	Beam radius	25.5 µm	Deflection velocity	> 4.5 mm/s
Wave length	1085 nm	Focal distance	330 mm	Rayleigh-length	1.44 mm

It is assumed that cooling of preforms, and thus secondary dendrite arm spacing, is affected by heat conduction through the shaft. Therefore, rod diameters from 0.2 mm to 1.0 mm are used for experiments to allow a wide spread in cooling conditions. For each rod diameter d_0 three different preform sizes d_P are generated so that the influence of both, the size of the preform and the rod diameter on the secondary dendrite arm spacing can be determined. The diameter of the largest preform of a certain rod diameter equals approximately the diameter of the smallest preform of the next larger rod so that the influence of heat conduction through the shaft can be determined, see Table 2.

Table 2. Diameters d_p of preforms with related laser power.

d_0 [mm]	1.0	0.5	0.4	0.3	0.2
P_L [W]	300	189	163	134	103
	3.45	2.51	1.73	1.18	0.85
d_p [mm]	3.10	2.21	1.49	1.05	0.72
	2.58	1.70	1.19	0.83	0.57

3.2. Upsetting of preforms in open dies

For the upsetting experiments, dies of 42CrMo4 hardened to 55 HRC are used. The lower die is separated in two parts with the section plane perpendicular to symmetry axis of the shaft of preform. A hemicycle notch is machined in both parts of the lower die so that the shaft of the preform can be inserted and clamped. The preform is fixed in the lower die so that the desired punch force can be applied. The initial height of the preform is reduced until a predefined punch load is reached. After unloading, the reduced height h_f of the preform as well as the flattened surface area A_f which has been in contact with the upper die are optically measured. For any value of k_f*, one forming operation is carried out without "reuse" of preform. The forming operation is carried out in a static materials testing machine "250 kN Allround RED" of Zwick GmbH und Co.KG. For punch forces ≤5 kN, a load cell "X-Force HP 5 kN" is used which allows accuracy class 1 for forces >10 N.

4. Results

4.1. Secondary dendrite arm spacing of preform

The secondary dendrite arm spacing is investigated to detect size effects in cooling behavior which might have an influence on flow stress level of preforms. The laser beam energy is brought into the rod and causes the preform formation. As soon as the laser beam is switched of, cooling of preform begins and heat dissipation from the liquefied preform to ambient atmosphere takes place by all three mechanisms, heat radiation, free and forced convection by shielding gas and heat conduction within the rod. Fig. 2a illustrates the secondary dendrite arm spacing plotted against the diameter of preform. The preforms with a quotient of upset ratio divided by rod diameter $s^*/d_0 \geq 135$ are marked with a dashed circle. The error bars related to each point show the standard deviation in S_D of the measurements of five primary dendrites. It can be derived that the preform with d_P=0.57 mm and d_0=0.2 mm has the smallest S_D with 8.30 µm. The largest S_D is reached at preforms with d_P=3.42 mm and d_0=0.50 mm with 28.97 µm. A trend is observed that the secondary dendrite arm spacing increases linear with increasing diameter of preform if only preforms with $s^*/d_0<135$ are taken into account. The linear regression function approximating the S_D is shown in Fig. 2a. If secondary dendrite arm spacings of preforms with $s^*/d_0 \geq 135$ are considered, a strong influence of rod diameter on S_D is detected. This can be seen e.g. at $d_p \approx 0.8$ mm, where S_D within the preform at d_0=0.3 mm is significantly smaller than S_D at d_0=0.2 mm.

4.2. Flow stress level of dendritic preforms

The flow stress level is a characteristic value with respect to forming operations. The lower the flow stress of a certain material, the lower also is the required tool load to plastify the work piece which allows cheap and easy to machine tool materials. On the other hand, a high flow stress level of the final work piece is desired when the mechanical load is expected to be high. Geiger et al. (2001) showed that the flow stress of equiaxed crystal microstructure is not only dependent on grain size but also on the size of the specimen. For preforms, the flow stress level k_f* is detected as proposed by Brüning and Vollertsen (2012). Fig. 2b shows the flow stress level k_f* plotted against the secondary dendrite arm spacing for various values of average natural strain φ*. The pictogram on the bottom right of Fig. 2b illustrates the secondary dendrite arm spacing S_D. It can be derived that k_f* decreases linearly with increasing S_D. This trend can be generally observed for all values of φ*, even with approximately the same gradient Δk_f^* which is $\Delta k_f^* = \delta k_f^* / \delta S_D = -7.5$ N/mm² µm. As expected, k_f^* increases with increasing φ^*. This shows that cold work hardening takes place due to strain induced formation of martensite.

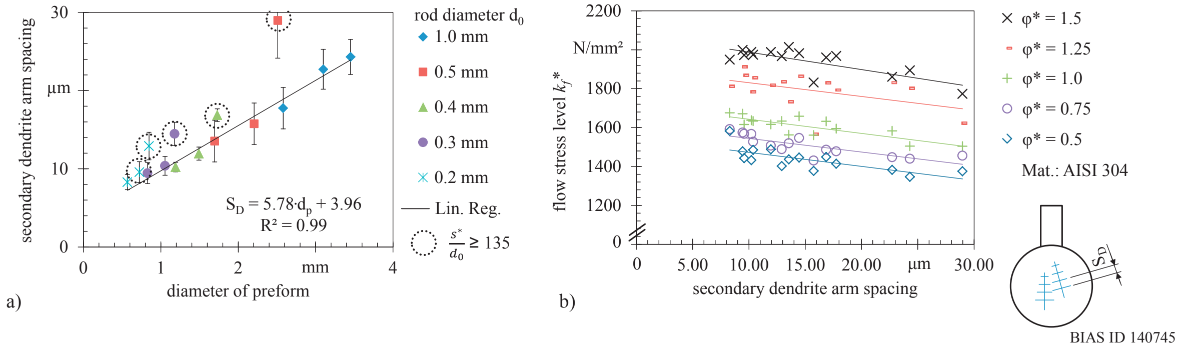

Fig. 2. (a) Secondary dendrite arm spacing S_D plotted against upset ratio s^* for different rod diameters; (b) flow stress level k_f^* plotted against secondary dendrite arm spacing for different values of average natural strain φ^*.

4.3. Influence of secondary dendrite arm spacing on surface topography

The surface of the preforms prior to forming operation is not homogeneously reflecting but rough. This can easily be detected when the preform is taken out of the experimental setup: the preform seems dim even though the surface is metallic and not oxidized which is due to the solidification of the liquefied metal at free surface. This condition combined with the fact that the material sets dendritic leads to the result that both, the primary and the secondary dendrites can be identified on the surface of the preforms, see Fig. 3a. The correlation between the lateral distance of the "buckles", which represent the ends of the secondary dendrite arms and their spacing S_D measured in cross-sectional polishes, is illustrated in Fig. 3b. The error bars show the standard deviation within measurements. It can be derived that there is a good correlation between both measuring options.

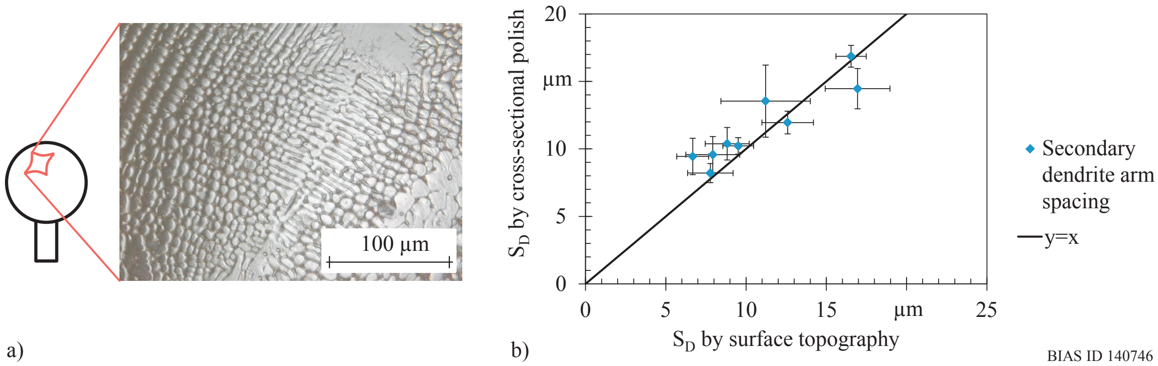

Fig. 3. (a) Detail of surface of preform with d_0=0.3 mm, P_L=134 W, d_P=0.811 mm, material: AISI 304 (1.4301); (b) Secondary dendrite arm spacing detected by cross-sectional polishes plotted against secondary dendrite arm spacing detected by surface topography.

4.4. Influence of forming operation on surface topography

The upsetting operation is carried out in open dies with surface roughness r_z=0.15 µm. The initial surface roughness of preforms with d_P=0.40 mm and d_0=0.2 mm is r_z=1.95 µm. Fig. 4a shows the surface roughness of that part of preform which has been in contact with the tools due to upsetting plotted against the average natural strain φ^*. It can be achieved that the surface is flattened by the forming operation as the surface roughness decreases almost linearly nearly until the surface roughness of the tool is reached. Fig. 4b and 4c show a top view of the preform at different forming steps. The flattening of the surface can be clearly identified.

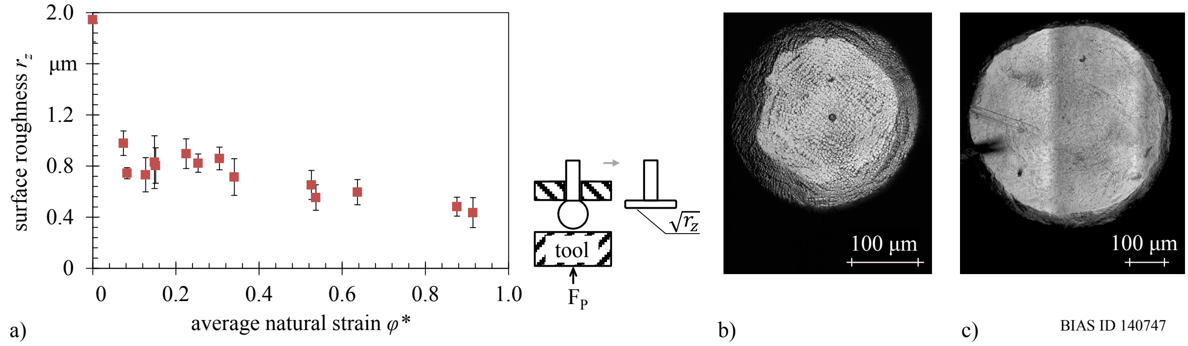

Fig. 4. (a) Surface roughness plotted against average natural strain; (b) Top view of preform at φ*=0.09. (c) Top view of preform at φ*=0.88.

5. Conclusion

Within this paper the influence of the diameter of the preform and the rod diameter on the micro structure is presented. It is shown that a size-effect caused change in secondary dendrite arm spacing S_D occurs taking effect on the flow stress level of the material. As a result, preforms with the same upset ratio have a different forming behavior. The secondary dendrite arm spacing is detected in two different ways. It is found that there is a good correlation between both measuring methods so that an analysis of surface topography gives already a good approximation of S_D. This fact is not natural as cooling conditions at the inside of the preform are assumed to be different to those at their surface so that S_D also could have varied. As a result of cross-sectional polishes, the secondary dendrite arm spacing reaches values between 8.30 µm and 28.97 µm. This significant difference leads to a decrease in flow stress level of about 6.5%. A linear correlation between secondary dendrite arm spacing and diameter of preform is observed for preforms with s^*/d_0<135 leading to the assumption that a rod diameter dependent limit in upset ratio s^* exists under which cooling of preforms is not influenced significantly by heat conduction within the rod. The initially rough surface of preforms is flattened when upsetting in open dies is carried out under the condition that the surface roughness of the dies is much lower than the initial surface roughness of the preforms. The flattening starts immediately so that already low values of average natural strain are sufficient to reduce surface roughness of preforms significantly.

Acknowledgements

The authors gratefully acknowledge the financial support by Deutsche Forschungsgesellschaft (DFG, German Research Foundation) for Subprojekt A3 "Stoffanhäufen" within the SFB 747 (Collaborative Research Centre) "Mikrokaltumformen – Prozesse, Charakterisierung, Optimierung".

References

Askeland, D., Phulé, P., 2006. The Science and Engineering of Materials. Nelson, Thomson Canada Limited.

Brüning, H., Vollertsen, F., 2012. Formability of micro material preforms generated by laser melting. Proc. 37th Int. Matador Conference, Manchester, Great Britain, 373-376.

Burr, A., Habig, K.-H., Harsch, G., Kloos, K. H., 1994. Handbook of Mechanical Engineering. London: Springer-Verlag.

Eichenhüller, B., Engel, U., Geiger, M., 2010. Microforming and investigations of parameter interactions. Prod. Eng. Res. Devel. 4, 135-140.

Geiger, M., Kleiner, M., Eckstein, R., Tiesler, N., Engel, U., 2001. Microforming. Annals of the CIRP, 50, 445-462.

Lange, K., 1988. Umformtechnik, Band 2: Massivumformung. Berlin: Springer-Verlag.

Lange, K., 2002. Umformtechnik - Handbuch für Industrie und Wissenschaft, Band 1. Berlin: Springer-Verlag .

Meßner, A., 1998. Kaltmassivumformung metallischer Kleinstteile: Werkstoffverhalten, Wirkflächenreibung, Prozessauslegung. Meisenbach Verlag: Bamberg.

Stephen, A., Vollertsen, F., 2011. Influence of the Rod Diameter on the Upset Ratio in Laser-based Free Form Heading. Steel Research International, Special Edition, 220-223.

Tschaetsch, H., 2005. Metal Forming Practise - Processes - Machines - Tools. Berlin: Springer-Verlag.

Vollertsen, F., 2008. Categories of size effects. Prod. Eng. Res. Devel. 2, 377-388.